A global assessment of piezoelectric actuated micro-pumps

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Abstract

This article provides an extensive outlook of different types of piezoelectric actuated micro-pumps published in the literature recently. We start by reminding the reader about the conventional operating parameters used to quantify the capabilities of these devices. After this introductory stage, we describe and classify the most prominent micro-pump's geometries found with piezoelectric actuation. At this point we identify the parameters given previously for each pump in order to establish a subsequent discussion in which the trends of different families are compared. Specific attention is given to the particularities of each case namely: flow-rates and back-pressures

Keywords: Piezoelectric, micro-pump, peristaltic, nozzle/diffuser valve, cantilever valve, ball valve, bridge valve.

1 Introduction

Micro-pump's applications are found in large variety of technology and science domains such as biology, medicine, electronics and space air crafting. They are used in micro total analysis systems (µTAS), portable DNA testing devices, electronic refrigeration systems and portable medication delivery appliances mainly for insulin distribution among others. As a rule, micro-pumps are designed and manufactured to meet a set of requirements on parameters whose importance may vary with the application; therefore it is very common to find significant differences from one to another. For example, in the field of drug delivery systems (DDS), it is known that the efficiency of some drugs is directly related to the way it is distributed [1]. In fact, some medications are more effective when they are injected into the body in definite concentrations. For this reason, micro-pumps designed for drug delivering purposes are required to pump particular quantities of fluid with high controllability [2], taking into account some other important particularities such as reduced size, low power consumption and biocompatibility [3]. Other applications may demand different features from micro-pumps. In the case of electronic cooling systems for example, the key points for designers are high flow rates and large pressure heads [4]. These qualities make the pump appropriated to be incorporated in the circuitry of modern electronic devices.
A significant selection of actuation principles is suitable to solve problems in domains where micropumps are normally used. Magnetohydrodynamic [5], electroosmotic [6], electrohydrodynamic [7], pneumatic [8], [9], electrostatic [10], [11], piezoelectric are some examples of the drivers most frequently employed in the design of these devices. A complete description of several types of micro-pumps can be found in [12]. However, piezoelectric actuation presents the particularity of being very likely to meet many of the requirements of a vast range of domains. Advantageous properties such as high integration capacity in micro-systems, low power consumption, high efficiency and high speed response make of piezoelectricity a very good choice for designers when it comes to design micro-pumps.
In comparison to devices with different actuation principles, piezoelectric micro-pumps can be designed to work at very high frequencies which translates to increasing flow-rates. This feature is in opposition to pneumatic or shape memory alloy actuation for example. In addition, piezoelectric ceramics present large force generation capacities and the ability of being synthesized and shaped at very small scale permitting their integration in micro-devices. These two last characteristics combined give the possibility to create powerful and small devices. Feature, more difficult to obtain with other type of actuators such as electromagnetic, thermopneumatic and magnetohydrodynamic.
In spite of these remarkable advantages, the main drawback of piezoelectric transducers is the low magnitudes of deformation and therefore of displacement, compelling the frequent use of amplifiers.

This article provides an outlook of the most recent piezoelectric micro-pumps found in the literature. The devices are presented and classified according to the type of motion applied to the fluid in order to create flow. For every geometry exposed in this paper, an analysis including their description, the elucidation of their working principle and the identification of their strengths and weaknesses with respect to the parameters used to quantify their performances is effectuated.
Mainly two actuating motions stand out in the family of piezoelectric micro-pumps which will give the guidelines to classify the different architectures. On one side, there is the reciprocating displacement or piston-like motion. On the other side, there is the peristaltic movement. Within the latter category, we find continuous and discrete types. They are differentiated essentially by the interruptibility of the forces applied on the fluid. Inside the reciprocating group on the other hand, the difference is made basically by the type of valves used to rectify the flow. Here, we find nozzle-diffuser valves, check valves and a variety of actuated valves.
Finally, a discussion is proposed. At this point, we mainly draw the attention to table 1 which summarizes the parameters of a variety of micro-pumps belonging to the categories presented before. At the beginning of this section, orders of magnitude of these parameters are presented and commented. This stage allows to constitute increasing or decreasing tendencies of certain variables according to the family of pump considered. At the same time, a comparison between different categories is carried out. Manifestly, this is done by keeping in mind the diversity of constraints and considerations made at the moment of designing and manufacturing.

2 Operating parameters

The very basic purpose of a micro pump is to displace a volume of fluid or gas from one place to another. For this reason, the parameters used to quantify the performance of such a device are related to the rate of fluid delivered per unit time and the maximum pressure under which the fluid can be moved.
When it comes to micro-pumps, the first concept that emerges is the maximum flow rate (Q_{max}). It quantifies the volume of liquid displaced per unit time when no pressure is exerted at the outlet.
However, this case never happens in operating circumstances since there is always some pressure acting in opposition to the flow. When it happens, the flow rate starts diminishing with the pressure exerted. Due to this reason, it is very important to characterize a micro-pump according to the maximum pressure it can work against, which is normally known as the maximum backpressure (p). This parameter can be more formally defined as the pressure developed at the outlet of the pump due to the increment in flow velocity generated by the pump [13].
At maximum backpressure, the flow rate becomes zero. Actually, Q_{max} and p give two points of a curve that provides an operation point for the pump. For a given pressure there is a unique value of flow rate and vice versa.
Another conventional parameter used to measure the performance of a micro-pump is the pump head (h). It corresponds to the work done on a unit weight of liquid passing from the inlet to the outlet. In its simplified form [15], the pump head is calculated as the difference of pressure between the inlet and outlet divided by the specific weight (ρg):

$$h = \frac{P_{out} - P_{in}}{\rho g}$$

Pump power (P_{pw}) is another parameter frequently used as well; it is defined as the power delivered to the fluid by the device, its value is calculated as the product of the backpressure and the flow rate.
Pump power leads to the concept of pump efficiency (η), which is basically the ratio between the pump power and the power required to drive the actuator. The difference between these two is due to three type of looses according to [3]. Fluid leakage losses which have direct impact on volumetric efficiency, frictional losses related to mechanical efficiency and losses due to imperfections in manufacturing associated to hydraulic efficiency. Therefore the total efficiency can be obtained from these three.
Authors usually report the operating voltage and the frequency at which the actuator is submitted, since superior discharge volumes and flow rates are achieved when resonant modes of the piezoelectric structure are employed at certain levels of voltage. Normally, piezoelectric drivers demand high voltages (60V – 1000V) due to the high electric fields required to deform the actuator considerably. Operating frequencies in the same way may vary significantly according to the operating principle and design.
Additional to these parameters, others like package size, power consumption and maximum force exerted by the actuator are commonly reported on literature according to their significance on the design which is highly related to the application domain and the pump's configuration itself.
At this point, it is worthwhile to remind the reader about the importance of the size of the pumping chamber since it plays a role in the order of magnitude of the pump parameters. Specifically, in cases where precision is demanded, the size of the pumping chambers tend to reduce in order to assure small

pumped volumes. [14] also indicates the influence of a varying backpressure in the dosing accuracy of a micropump concluding that the pressure-dependent flow curve should be sufficiently flat to ensure an accurate dosing at varying outlet overpressure.

3 Reciprocating micro-pumps

The operation of this type of micro-pump is based on the change in volume of a two openings-reservoir containing a fluid. This volume change is better known as stroke volume (ΔV). In contrast to the stroke volume, there is the dead volume which corresponds to the quantity of liquid that remains in the pump when the chamber volume is minimal over a pumping cycle. The ratio of stroke volume and dead volume constitute a parameter known as compression ratio which is quite related to the pump's performance. A schema of this architecture is shown in figure 1.

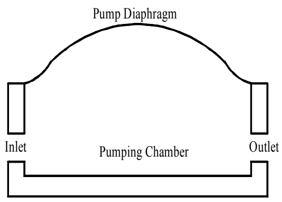

Fig. 1. Reciprocating Micro-pump

The rectification of the flow is normally effectuated by valves that according to their operating principle and geometry increase or reduce the complexity, power consumption and performance of the pump. For this reason, it is very important to subdivide this category under the criterion of the type of valves used. Three main types of valves are noticeable in reciprocating geometries. In a first place, there are the nozzle-diffuser valves which utilize exclusively particular shapes and geometries to direct the flow. Consequently, no moving parts are present. A second group is determined by the check valves, which posses moving parts and control the flow according to its direction. They privilege streams traveling in certain directions. Finally, there are the actuated valves which utilize external power sources to generate direct mechanical action on the fluid.

When a reciprocating micropump is driven by piezoelectrics, it becomes very interesting to work at frequencies close to the resonance of the actuator in order to obtain higher displacements and consequently higher stroke volumes. Here, it is important to consider the viscosity of the fluid. [16] and [17] propose a modal analysis of the piezoelectric transducer to establish the frequency at which the maximum stroke volume is obtained.

The core of a reciprocating micro-pump is undoubtedly the pumping chamber along with the pump membrane or pump diaphragm. The device's performance is directly related to the physic characteristics of these two latter. [18] illustrates the calculation of stroke volume according to different deflections patterns of the pump diaphragm for a cylindrical chamber. These computations will lead to the estimation of most of the parameters of this type of pump.

Some authors like [19], design their devices to work at the resonant frequency of the pump diaphragm in order to improve the flow rate and the efficiency. At low frequencies, it can be assumed a linear relation between flow rate and pumping frequency (f), assuming a fluid displacement in one direction only:

$$Q = \Delta V \cdot f$$

3.1 Reciprocating micro-pumps with nozzle/diffuser valves.

The idea behind this geometry is to exploit the direction dependent behavior of tapered channels to rectify the flow. Two principal advantages stand out in micro-pumps having this type of valves. Firstly, nozzle/diffuser configuration avoids the clogging problem of moving valves. Secondly, structures become simpler reducing in this manner manufacturing complexity and costs. The main drawback of this type of micro-pumps is its low efficiency since there is a considerable amount of fluid re-entering the pumping chamber in a single pumping cycle.

The performance of the rectification capability of a nozzle/diffuser configuration is measured by the ratio of the pressure loss at the inlet and the outlet (η_{nd}). This value depends on the geometry of the nozzle/diffuser [20] (Diameter, length and tapper angle) and on the fluid characteristics (Kinematic viscosity, Reynolds number and flow velocity). Its magnitude is given by:

$$\eta_{nd} = \frac{19\,\mathrm{Re}_n}{20\,\mathrm{Re}_d \left[\left({D_0}^2 \big/ {D_1}^2 \right)^{0.5} \right] \left[\left({D_1}^2 \big/ {D_0}^2 \right)^{0.33} \right]}$$

With Re_n, Re_d, D_0 and D_1 standing for the Reynold's number of the nozzle, the Reynold's number of the diffuser, the diameter of nozzle and the diameter of diffuser respectively.

For nozzle/diffuser geometries, the flow rate can be calculated as:

$$Q = 2 \cdot \Delta V \cdot f \, \frac{\sqrt{\eta_{nd}} - 1}{\sqrt{\eta_{nd}} + 1}$$

Different applications can be found for nozzle/diffuser pumps. [21] exposes a micro-pump designed to supply ethanol to a fuel cell with a flow rate requirement is about 0.31 ml/minute if using a methanol water solution as fluid. [22] reveals a device conceived for fuel dosing in automobile heaters with the particularity of having a micro filtering system embedded at the inlet. [17] moves to the field of medicine and proposes a micro-pump applied on an invitro injection system for diabetics. The author highlights the possibility of pumping gases and liquids, high reliability and low sensitivity of drug particles due to the lack of a moving valve.

Many approaches have been reported to improve the performance of this type of pumps. [23] presents a reciprocating micro-pump with high compression ratio composed of a shallow pumping chamber made from Silicon, a thin pumping diaphragm and a set of deep diffusers that according to the author improves the efficiency of the device. [24] mentions similar statements about better performances of reciprocating micro-pumps when the thickness of the diaphragm is reduced. Actually, this article discusses the impact on flow rate when parameters like diffuser's geometry, excitation voltage and frequency are modified. All parameters involved in the optimization process are set in order to maximize the performance of the final architecture. An original improvement to the nozzle/diffuser geometry is proposed by [25]. Here, the classic tapered shape of the channels are modified by adding vortex areas along the fluidic pattern, which is, a sequence of rounded and sharp bifurcations added along the nozzle/diffuser path. The author claims to reduce the tendency of the flow to re-enter the pumping chamber and makes a comparison with a classical nozzle/diffuser geometry reporting an increment of efficiency of up to 2.9 times at maximum flow rate conditions. [26] suggests a change in the geometry of the cross section of the nozzle/diffuser and studies its effect on the pump's performance. Other authors propose deep changes to the classic structure of this type of pump. [27] unveils a three dimensional architecture where the nozzle and the diffuser are not placed in the same plane claiming to be a suitable approach to generate pre-assembled valveless micro-pump structure.

3.2 Reciprocating micro-pumps with check valves

Check valves are those whose operation is defined by the direction of the flow. In fact, when they are embedded in a reciprocating structure, the forces created by changes in pressure inside the pumping chamber during a pumping cycle move a two-position mobile which allows or stops the fluid's circulation.

According to piezoelectric micro-pump's literature so far, the mobile can take mainly three forms as shown in figures (2a), (2b) and (2d):

First (figure 2a), there is the ball-valve type where the mobile is a ball which blocks an opening by the action of the fluid's pressure exerted on it. Similarly, when the flow goes in the opposite direction, the pressure of the fluid removes the ball away from the opening allowing liquid to pass. An example of this geometry is given by [28]. The paper presents micro-pump made with a stereolithographic technique composed of steel balls of 1,2 mm diameter and a valve stopper of 0,5 mm diameter. Additionally, an approach aimed to predict the performance of a ball valve micro-pump versus the working frequency according to its geometrical and mechanical characteristics is discussed.

In the second place (figure 2b), there is the flap-valve. The operating principle is exactly the same as that of ball-valves. However in this geometry, the mobile is replaced by a cantilever beam fixed at one of its tips. The beam bends upwards/downwards allowing circulation or remains straight blocking it. All according to the flow direction. The design and study of this type of geometry is accomplished by considering the dynamic behavior of the device. In fact, many authors rely on the great displacements obtained on the cantilever beam when it is driven at its resonant frequency. [29] for example, presents a micro-pump with flap valves and an innovative diaphragm geometry. The author models this latter with a classic mass-damper-spring system and makes use of the harmonic resonance of the working fluid along with the system components to drive the whole at a frequency that optimizes the device's performance. As conclusion of the work, it is claimed that better results were obtained by using narrow valves. In a similar way, [30] makes a discussion in his work about the influence of the resonant frequencies of the valves and the actuator in the performance of the micro-pump. Actually, the author draws attention to the maximum flap valves efficiency observed when they work at their resonant frequency and the impact on the pump’s flow rate. The author claims as well a peak in the device’s performance when it is driven at the resonant frequency of the piezoelectric actuator, suggesting multiple optimal frequencies at which the pump can work.

Other authors rely exclusively on the resonant frequency of the actuator. [31] for example, increases the inertial mass of the piezoelectric transducer in order to adapt its resonant frequency for a pumping application. As final example of this type of micro-pump, there is that presented by [32]. The core of his

design is a domed shaped diaphragm which is supposed to release extra pressure due to the residual stress stored in the domed shape.
Finally (figure 2c), there are the bridge-valves that work very closely to the flap ones. Here, the opening is blocked by a plate attached to the structure of the pumping chamber by four micro-springs located in every corner. Again, if the flows goes in the right direction, the plate goes up allowing circulation through the gap between it and the valve stopper. Otherwise, the flow is blocked by the plate itself. This type of valves present a more complicated manufacturing process, however they are claimed to support great values of pressure. In fact, [33] discusses the tendency of flap valves to fail under extreme high pressures and the convenience of having four contact points with the pump structure instead of one which is the case of the flap-valve. The author presents a micro-pump actuated by a piezoelectric stack supporting 350 PSI at 10 kHz. [34] proposes in a similar way a valve composed of a disc over a compliant orthoplanar string with four folded arms made from SU-8 which is an epoxy-based negative photo-resist. This material has the advantage of high flexibility so the micro-strings require less fluid pressure to work. The pump unveiled in this article operates at 1 mL/min at a pressure of 200 mm of water.
In general, reciprocating pumps with check valves have better performance than those with nozzle/diffuser. They are known for having high compression ratios and high pump pressures [35].

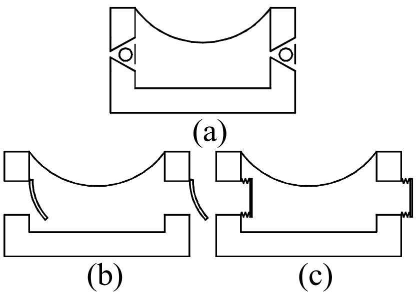

Fig. 2. Check valves. (a) Ball, (b) Flap, (c) Bridge

3.3 Reciprocating micro-pumps with actuated valves

In addition to the compulsory need for external sources of energies to create motion on a fluid in mechanical micro-pumps, this category uses also actuating forces to rectify the flow. Characteristic aspects of this type are: the increased complexity of the device due to the electronics embedded to control the opening and closing sequences of the valves. There is also the extremely high pressures stood by the pump and consequently high efficiency values which is a direct consequence of the fact that the valve blocking is done by external actuators.
Actuated valves are employed normally for specific applications. For example, [36] exhibits a pump conceived for a medical application. More specifically, it is applied in a novel sphincter system composed by a cuff system which inflates or deinflates with a biological compatible fluid replacing in this way a weaken sphincter muscle. The micro-pump used in this application moves fluid inside the cuff system. Therefore, high flow-rates to allow rapid artificial muscle contractions and high pressures (around 30 kPa) are required. The valves and the pumping chamber of this device are actuated by piezoelectric patches. The valves have also a nozzle/diffuser geometry that increases even more the performance of the pump. The author highlights features such as biocompatibility and high pressure (60 kPa at 1,8 mL/min).

4 Peristaltic micro-pumps

The word peristaltic comes from the Greek peristaltikos which relates the movement caused by propagating muscular contractions that take place in the intestines. The same basis is then applied to create fluid flow. This principle is often found in piezoelectric actuated micro-pumps either under the form of multiple pumping chambers connected in series actuated harmonically by independent sources, or, under the form of a flexible channel whose deformation follows a mechanical travelling wave motion. These arrays can either be linear or circular. There are two types of structures of peristaltic micro/pumps.

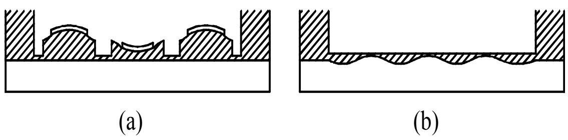

Fig. 3. Peristaltic micro-pumps. (a) Discrete geometry, (b) Continuous geometry.

The first corresponds to a discrete or discontinuous geometry since the excitation is localized on several independent points (figure 3a). The second on the contrary, depicts a continuous architecture in which the motion is applied over the entire structure (figure 3b). A remarkable feature of this type of micro-pump is the absence of valves that makes of this category a good choice when manufacturing simplicity is an issue.

4.1 Discrete peristaltic micro-pump

This geometry is basically an array of multiple reciprocating pumping chambers (at least three) connected in series and actuated sequentially to move the fluid in one direction or other. The principal advantage of this architecture is the possibility of reversing the pumping direction. However, it suffers from the same inconvenient of the nozzle/diffuser reciprocating micro-pump, which is low efficiency caused by fluid re-entering the pumping chambers. Additionally, there is an increment in power consumption and the necessity of having a control system to generate the pumping sequence.
The stroke volume is calculated following the same approach as for reciprocating pumps consequently the frequency at which the device is actuated is a critical issue for design. [37] proposes a 12 µL/min micro-pump with a maximum back pressure of 3 kPa composed of three pumping chambers applied to the control of biosamples. The author discusses the effect of the membrane resonant frequency on the device's performance and utilizes it as a mean to obtain the optimal pumping sequence speed. Similarly, [38] and [39] suggest a relationship between the actuator activation sequence and the resonant frequency of the diaphragm. The author reports a change in resonant frequencies of diaphragm when the sequence varies. Subsequently, the flow rate is affected.
Another very interesting geometry that can be inscribed in this family of pumps is proposed by [40]. Here, a mechanical traveling wave motion is created by an array of piezoelectric transducers placed under a flexible channel actuated in such a manner that they deform the walls of this latter creating in this way a peristaltic motion. The maximum flow rate generated by this micro-pump is 1 µL/min.

4.2 Linear peristaltic micro-pump

In this configuration, the motion of fluid is generated by the action of a mechanical travelling wave deflecting the walls of the pumping chamber. The principal characteristic of this type of micro-pump is the high frequencies of operation which are usually greater than 20 kHz. Normally the geometries belonging to this category are simpler and do not require additional controllers to generate sequences. The drawback lies on the difficulty to obtain a mechanical travelling wave in a finite elastic medium. [41] has registered a patent of a micro-pump following this principle claiming as advantages the simplicity, the absence of moving parts and a great capacity of integration.

5 Discussion

The table 1 exposes the principal characteristics of several micro-pumps published over the last two decades. A variety of characteristics, operating conditions, material and performances can be observed.
At this stage, it is possible to make some inferences about the order of magnitude of the most significant parameters of micro-pumps.
For example, when it comes to flow-rate, the most diversified ranges are found in pumps having nozzle-diffuser and cantilever valves. Their magnitudes go from some µL/min to some thousands of µL/min. This fact makes of them the most heterogeneous categories. Micro-pumps having actuated valves and those peristaltic posses more uniform values of flow-rates. They lay around tens of µL/min and some thousands of µL/min respectively.
When magnitudes of back-pressure are considered, nozzle-diffuser are once again the most varied family. Here, their values range between few Pa and thousands of Pa. Peristaltic pumps on their own side work in the range of hundreds to thousands of Pa. Finally, for pumps having cantilever and actuated valves, the back-pressure range is about several thousands of Pa.
The orders of magnitude of micro-pump's package size were determined from examples published in literature likewise. Sizes of devices using nozzle-diffusers lay around the same range, namely, few mm^3. To site some examples, there are those from [22], [25] and [27]. Peristaltic pumps exist within a range between some tens of mm^3 [43] and few tens of cm^3 [37]. Last, micro-pumps having actuated valves and cantilever valves show similar size characteristics. The average order of magnitude is located around few mm^3 as it is exemplified by [31] or [36].
Voltage levels on the contrary are very uniform in general, they vary around one hundred volts. However, exceptionally, they can take small values as in the pump reported by [36].
We remind the reader at this point that there is no indication that a new or existing pump could not take values beyond the limits presented here. Since, these were based on few available examples that belong to a large population.
When the magnitudes presented in table 1 are observed more narrowly, it is noticeable that no huge differences between different categories appear. However, certain generalizations can be made. Manifestly, this generalizations are not meant to work

as rules since clever designs, bigger pumping chambers and other innovations can improve the performances of certain geometries over others. For example, the highest back-pressures are detected in reciprocating micro-pumps having actuated valves and cantilever valves which is coherent with the description given previously. The maximum value found on the table regarding back-pressure is provided by the pump published by [31] which belongs to the cantilever type-valve. This device was designed to work at the resonant frequency of a mass-piezostack system which increments dramatically the inertial mass and the pump power supplied to the fluid.
It is also interesting to highlight the high values of flow rate in structures conceived to avoid fluid re-entering the pumping chamber. Those are reciprocating pumps with actuated valves, bridges and cantilevers.
Additionally, standing out among all the examples given in this article, there is the pump reported by [21] which despite belonging to a geometry that by nature is not likely to have high flow rates, presents the highest value. Two factors might explain this situation. One one side, there is the fact of driving the whole loaded device at its resonant frequency (fluid included). On the other side, there is the relative large volume of the pumping chamber which allows important amounts of fluid displaced per pumping cycle. Another remarkable example is the pump presented by [25] who reports a 10900 Pa nozzle/diffuser micro-pump. This feature can be explained by the vortex areas added to the classic nozzle/diffuser path increasing in this way the ability of the device to stand higher pressures .
As for the rest of the nozzle/diffuser micro-pumps, the expected behaviour is evidenced namely, modest flow rates and back-pressure values.
As last comment, there is a trend among designers to work with Silicon due to the vast diffusion of this material in the manufacturing of micro-systems.

6 Conclusions

We have presented an article aimed to give an understanding and a global view of the different and most popular types of piezoelectric micro-pumps reported so far. Starting with the basic concepts about the characterization of these devices, we have made a tour over a variety of families highlighting every time the most notorious features and some designing principles.
Several examples were presented through the paper as well as a brief discussion over the generalizations and tendencies of every architecture.
Regarding piezoelectric actuated micro-pumps literature, it was rather clear that the reciprocating devices were the most frequently reported. In fact, most of the examples given in this article belong to this category. Advantages like manufacturing ease, intuitive functioning and adaptability to multiple applications make of this type the most evident choice for designers when a micro-pump is needed. The tendency in general is to go for the simplest structure, evidence of that is the high number of publications regarding reciprocating piezoelectric pumps having nozzle/diffuser valves. At this point it is worth to say that every micro-pump was designed for a purpose and there is no superiority from one to another. Every family has defined features that are more or less adaptable to certain utilizations and operating conditions.

Table 1. Comparison of piezoelectric actuated micro-pumps

Author/Year	Type	Flow Rate (μL/min)	Backpressure (Pa)	Vpp Voltage (V)	Frequency (Hz)	Working Fluid	Material	Application
L.-S. Jang et al. 2007 [38]	Peristaltic	36.8	520	100	700	Water	Si/ Pyrex glass	Unknown
D.S. Lee et al. 2004 [37]	Peristaltic	12	4700 (Estimated from the curves)	120	10	Unknown	Si/Glass	Biology
TT. Zhang et al. 2006 [21]	Nozzle Diffuser	5000	1000	100	200	Water	Hard Plastic	Fuel Cells
C. Yih-Lin et al. 2007 [27]	Nozzle Diffuser	1.1	16.7	Unknown	10000	Water	Ciba FC 52 Isocynate/52 Polyol	Propulsion System
Zhiliang Wan et al. 2001 [42]	Nozzle Diffuser	900	2614	3	7000	Insulin	Si/Glass	Drug Delivery Systems
T. Gerlach et al. 1995 [26]	Nozzle Diffuser	320 (Estimated from the curves)	7000 (Estimated from the curves)	Unknown	5000	Methanol	Si	Unknown
I. Izzo et al. 2006 [25]	Nozzle Diffuser	620	10900	100	2250	Water	Si	Unknown
Q. Cui et al. 2006 [24]	Nozzle Diffuser	40	1960	100	400	Water	Si/Glass	Drug Delivery Systems
G.H. Feng et al. 2005 [32]	Nozzle Diffuser	3.2	120	80	80000	Water	Si ZnO Parylene	Drug Delivery Systems
H. K. Ma et al.2007 [29]	Actuated Valves	700	4900 (pressure head At Q=0)	50	100	Water	Al/PDMS	Heat Dissipation/Fuel Cells
A. Doll et al. 2006 [36]	Actuated Valves	1800	60000	4.5	17	Water	Si	Medical Implant
J. Kan et al 2005 [30]	Cantilever	3500	27000	50	3000	Water	PMMA	Drug Delivery Systems
J.H. Park et al. 1999 [31]	Cantilever	80	320000	45	2000	Water	Nickel	Unknown
N.T. Nguyen et al. 2003 [34]	Bridge	1000	1960	150 (Estimated)	140	DI Water	SU-8/PMMA	Unknown

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